High Resolution Wide Dynamic Range Distance Sensor using Spatial Signal Processing

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ABSTRACT

This paper presents a non-intrusive, non-contact object distance mapping sensor using an Electronically Controlled Variable Focus Lens (ECVFL). The proposed sensor is a free-space-based optical sensor that uses ECVFL-based agile optics to direct light from a object that requires terrain height mapping. The presented compact design makes the proposed sensor ideal for use in environments where laser illuminated objects are in a hazardous environment such as in environments with radiation, heat, cold, harmful machine parts, etc. The proposed design uses a few optical components and smart detection optics for making its object distance/terrain measurements. The presented sensor can find potential remote sensing applications in ground and space vehicle maneuvering, machine parts inspection and in chemical, transportation and aerospace industries.

Keywords: Optical Instrumentation, Electronic Lens, Distance Sensor

1. INTRODUCTION

Distance sensors are used in a variety of applications. There are a variety of methods used in distance sensors. These include the use ultrasonics [1], RF radar [2], laser radar and other optical methods using electrically modulated light [3]-[7]. These prior art methods require the use of time-frequency modulation. This can be beneficial depending upon the application it will be used in, but in some cases the sensor's hardware requirements lead to a complex, high-cost system. An industrial application for distance sensors has been in liquid level sensing. In this area, contact based optical [8]-[21], electrical [22]-[23] and ultrasonic [24] sensors have been proposed to measure the liquid level. The problem with these liquid level sensors is that they require a wired interface and require contact with the sample. In applications where caustic, toxic, volatile, or cryogenic liquids are used, this physical contact is not desirable and a non-contact method would be preferred. Optical triangulation is such a freespace optical non-contact method [25]. In addition, recently, another noncontact distance sensor using spatial signal processing has been proposed and demonstrated [26]-[28]. The present paper extends this spatial processing-based distance sensing method by combining it with optical triangulation to further improve the sensor resolution.

2. PROPOSED DISTANCE SENSOR

The prior art distance sensor [26] is shown in Fig. 1. A laser source travels through a Beam Splitter (BS) and an Electronically Controlled Variable Focus Lens (ECVFL) where the ECVFL focuses the beam of the target. The beam is reflected by the target and traces the path of the incoming beam back to the BS. Here part of the beam is directed to the CCD camera. By tuning the ECVFL focal length F so that the minimum spot occurs on the CCD, the distance of the target D_T can be found using geometrical optics as described in ref. [1] or more accurately using Gaussian beam analysis.

To solve for the distance of the target, the sensor system can be described using ABCD Gaussian beam analysis [29]. The ABCD matrix of the sensor system can be found as:

$$M = \begin{bmatrix} 1 & L_4 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/F_s & 1 \end{bmatrix} \begin{bmatrix} 1 & L_2 + L_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/F & 1 \end{bmatrix} \begin{bmatrix} 1 & 2D_T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/F & 1 \end{bmatrix} \begin{bmatrix} 1 & D_0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad (1)$$

Photonic Applications for Aerospace, Transportation, and Harsh Environment II, edited by
Alex A. Kazemi, Bernard Kress, Eric Y. Chan, Nabeel A. Riza, Lothar U. Kempen, Proc. of SPIE
Vol. 8026, 80260D · © 2011 SPIE · CCC code: 0277-786X/11/$18 · doi: 10.1117/12.885957

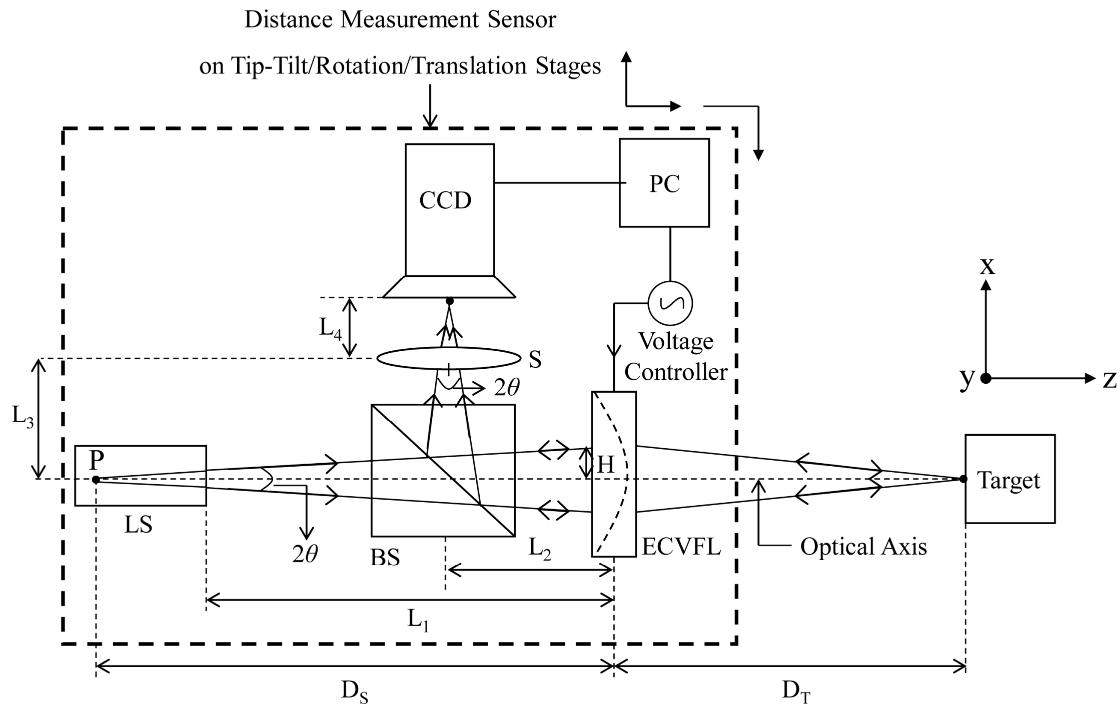


Fig. 1 The noncontact distance sensor using spatial signal processing.

where L_2, L_3, and L_4 are system parameters for distances shown in Fig. 1, F_s is the focal length of lens S, F the focal length of the ECVFL, D_T the distance to the target and D_0 is the location of the minimum beam waist. Now the complex q-parameter can be written as:

$$\frac{1}{q_1} = \frac{1}{R(z)} - j\frac{\lambda}{\pi w^2(z)} = \frac{Cq_0 + D}{Aq_0 + B} = \frac{ACz_R{}^2 + BD}{A^2 z_R{}^2 + B} - j\frac{z_R(AD - BC)}{A^2 z_R{}^2 + B} \tag{2}$$

which leads to the beam waist being:

$$w^2(z) = \frac{\lambda}{\pi}\frac{A^2 z_R{}^2 + B^2}{z_R} \tag{3}$$

From equations (1)-(3), the appropriate F for a minimum beam size to occur on the CCD can be found.

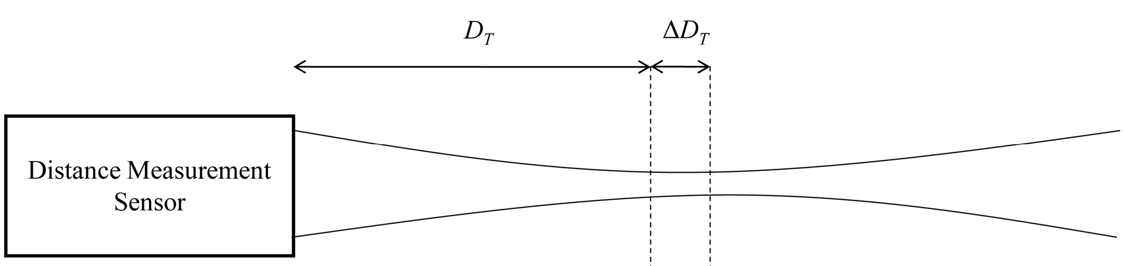
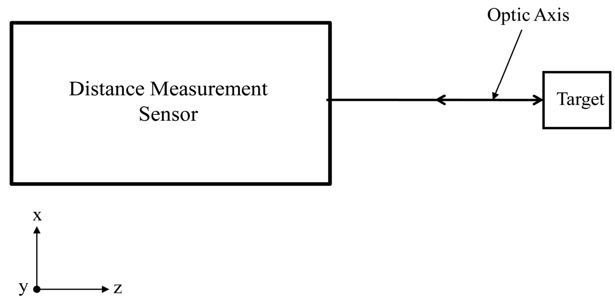
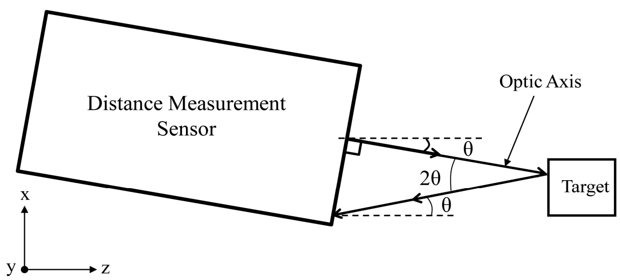


Fig. 2. Distance measurement resolution limit of the prior-art spatial processing-based distance sensor.

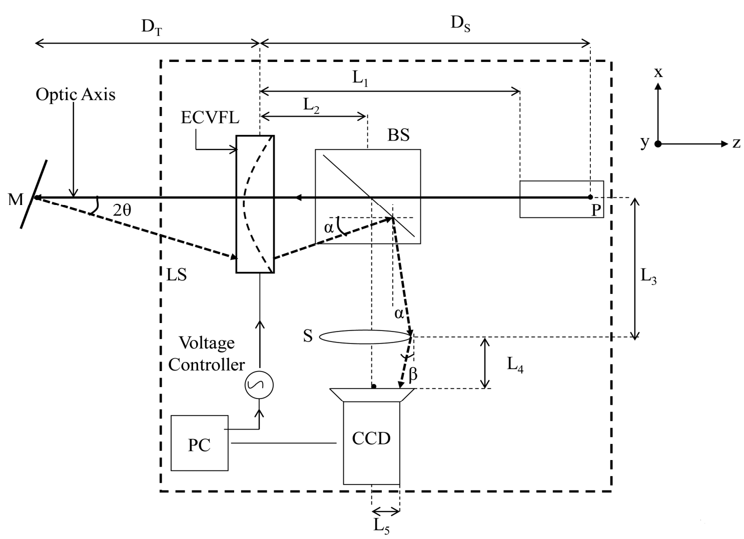
Note that as shown in Fig. 2, Gaussian laser beam diffraction fundamentally limits the best axial (or distance measurement) resolution of the sensor system to the range ΔD_T. This assumes that the change in focal length of the ECVFL via electronic signal control is fine enough but that beam diffraction limits the ultimate resolution ΔD_T.



(a)



(b)



(c)

Fig. 3. The proposed spatial processing-triangulation high resolution distance sensor with (a) the optic axis perpendicular to the target, (b) making an angle 2θ with respect to the optic axis of measurement shown in (a), and (c) the trace of the beam path through the sensor system.

To get a finer distance measurement not limited by beam diffraction, this paper for the first time demonstrates a novel distance sensor design (see Fig.3) that makes use of classic optical triangulation method in combination with the Fig.1 sensor system spatial processing. As shown in Fig. 3(a), first a measurement of the target distance is made with the optic axis perpendicular to the target. Then as shown in Fig. 3(b), the entire distance sensor assembly is tilted so that the optic axis is now at an angle θ with respect to the original direction of the optic axis. Since tilt of the example target mirror and the tilt of the distance sensor assembly can be interchanged, Fig. 3(c) shows how the return ray from the target would trace through the sensor system. Upon reflection from the target, the returning ray makes an angle 2θ with respect to the z-axis. This ray then travels through the ECVFL which causes the light to bend at an angle α which using geometrical optics is found to be:

$$\alpha = 2\theta \, D_T \left[\frac{1}{F} - \frac{1}{D_T} \right] . \tag{4}$$

Now after reflection from the beam splitter, which is at 45º with respect to the z-axis, the ray hits the lens S at an angle α a distance from the center of the lens S with focal length F_S. Using geometry, the angle after the lens S is found to be:

$$\beta = -\alpha - \left[L_2 - \frac{2\theta D_T}{\alpha} \right] \frac{1}{F_s} . \tag{5}$$

The distance that the beam moved on the CCD is found to be:

$$L_5 = L_2 - \frac{2\theta D_T}{\alpha} - \alpha\left(-2\theta \, D_T + L_3\right) + L_4 \tan(\beta) . \tag{6}$$

As the tilt angle of the entire sensor system (or for present analysis, the target mirror) is known and the beam motion on the CCD has been measured, via a prior sensor calibration table, the exact target distance can be determined. This operation assumes that the sensor has already been calibrated for its many coarse bins that were limited in beam size due to beam diffraction. Within each coarse bin, one implements triangulation for the proposed sensor to get a finer reading of the target distance D_T.

3. EXPERIMENT

The proposed sensor design of Fig. 3 is assembled in the laboratory using a 632.8 nm HeNe laser source, a target mirror, and with distances D_s = 19.85 cm, L_1 = 17.3 cm, L_2 = 9 cm, L_3 = 8.3, L_4 = 4.76 cm, and F_s = 10 cm. The target mirror is placed at a target distance of 16.5 cm that falls with the sensor calibrated coarse bin that gives the initial sensor detected target distance to be 16 cm. This coarse bin is observed by creating the minimum laser beam spot size as seen via the CCD (see Fig. 4(a)) that is formed on the target mirror by adjusting the voltage of the ECVFL. Next for determining the target distance with high resolution, the target mirror was tilted by 5 arcseconds and the laser spot moved on the CCD plane as shown in Fig. 4(b). In this case, the tilted target reflected beam was hitting the edge of the ECVFL and hence the paraxial approximation did not hold for proper distance processing given the rotation resolution limit of the target rotation stage. So the solution is to use a larger diameter ECVFL.

As this larger aperture ECVFL was not available in the laboratory, an alternate sensor test design shown in Fig.5 was implemented in the laboratory using two separate ECVFLs. A second CCD is used to make sure that the target reflected beam size is still a minimum for a given target distance location. For example, the smallest beam size seen in Fig. 6(a) is formed when the ECVFLs are set for F = 22.5 cm which gave a coarse target distance of 87 cm. This coarse reading was 1 cm away from the actual target distance which is 86 cm. The target mirror was tilted by 4 degrees and 25 arcseconds and the beam moved a distance L5 = 13.2 cm. Based on the sensor calibration, this gave a target distance of 85.96 cm.

Fig. 4. The distance sensor with (a) the optic axis perpendicular to the target (b) making an angle 2θ with respect to the optic axis of measurement shown in (a) and (c) the trace of the beam path through the optical system.

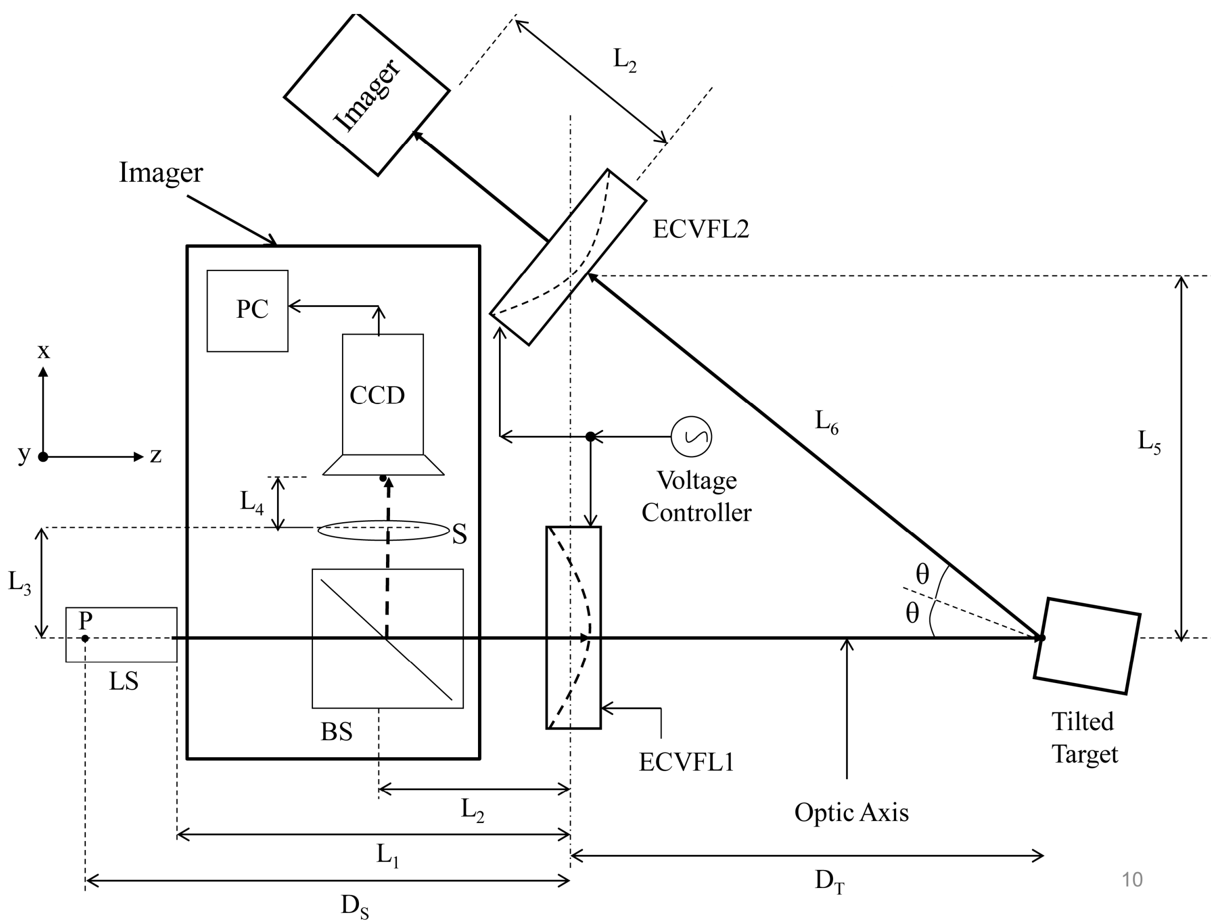
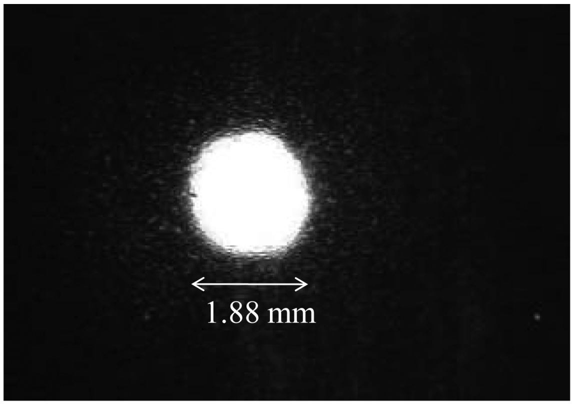


Fig. 5. The experimental distance sensor.



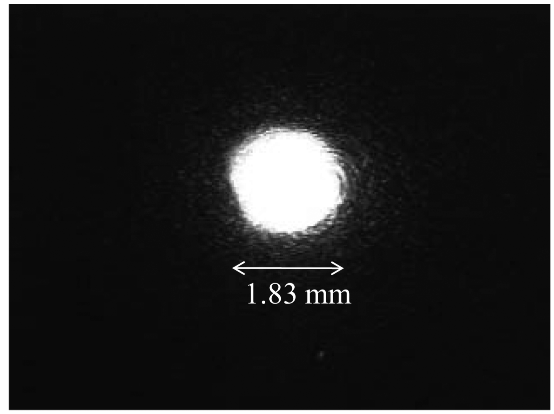


Fig. 6. The experimental data using the sensor setup of Fig. 5.

4. CONCLUSION

For the first time, demonstrated is a noncontact high resolution distance sensor using ECVFL-based spatial signal processing and optical triangulation. The sensor can be optimized by using the appropriate aperture size ECVFL to enable hardware minimal sensor design. Future work relates to demonstration of such an optimized distance sensor that avoids use of costly RF electronics and light time/frequency modulation.

5. ACKNOWLDGEMENTS

The authors would like to thank Nuonics, Inc. for hardware support.

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